Flight Test Evaluation of Tactical Synthetic Vision Display Concepts in a Terrain-Challenged Operating Environment

Randall E. Bailey*, Russell V. Parrish**, J.J. (Trey) Arthur III†, and R. Michael Norman‡

NASA Langley Research Center, Hampton, VA

ABSTRACT

NASA's Aviation Safety Program, Synthetic Vision Systems Project is developing display concepts to improve pilot terrain/situational awareness by providing a perspective synthetic view of the outside world through an on-board database driven by precise aircraft positioning information updating via Global Positioning System-based data. This work is aimed at eliminating visibility-induced errors and low visibility conditions as a causal factor to civil aircraft accidents, as well as replicating the operational benefits of clear day flight operations regardless of the actual outside visibility condition. A flight test evaluation of tactical Synthetic Vision display concepts was recently conducted in the terrain-challenged operating environment of the Eagle County Regional Airport (Colorado). Several display concepts for head-up displays and head-down displays ranging from ARINC Standard Size A through Size X were tested. Seven pilots evaluated these displays for acceptability, usability, and situational/terrain awareness while flying existing commercial airline operating procedures for Eagle County Regional Airport. All tactical Synthetic Vision display concepts provided measurable increases in the pilot's subjective terrain awareness over the baseline aircraft displays. The head-down display presentations yielded better terrain awareness over the head-up display synthetic vision display concepts that were tested. Limitations in the head-up display concepts were uncovered that suggest further research.

Keywords: Synthetic Vision, Controlled Flight Into Terrain, Terrain Awareness, Synthetic Image, Head-Up Display

1. INTRODUCTION

In commercial aviation alone, over 30% of all fatal accidents worldwide are categorized as Controlled Flight Into Terrain (CFIT), where a mechanically sound, normal functioning airplane is inadvertently flown into the ground, water, or an obstacle, principally due to the lack of outside visual reference and situational awareness (Reference 1). The Synthetic Vision Systems (SVS) project, under NASA's Aviation Safety Program (AvSP), is developing technologies with practical applications that will eliminate low visibility conditions as a causal factor to civil aircraft accidents (Reference 2) while replicating the operational benefits of clear day flight operations, regardless of the actual outside visibility condition.

1.1 Synthetic Vision Display Concepts

A major thrust of the SVS project involves the development and demonstration of affordable, certifiable display configurations which provide intuitive out-the-window terrain and obstacle information, including guidance for navigation and obstacle avoidance, for Commercial and Business aircraft. In addition to forward-fit applications, a path

* NASA/LaRC, 24 West Taylor St. Hampton, VA 23681, r.e.bailey@larc.nasa.gov, phone: 757-864-8682

** NASA/LaRC, 24 West Taylor St. Hampton, VA 23681, r.v.parrish@larc.nasa.gov, phone: 757-864-6649

† NASA/LaRC, 24 West Taylor St. Hampton, VA 23681, j.j.arthur@larc.nasa.gov, phone: 757-864-6609

‡ Boeing Phantom Works, East Wardlow Rd., Long Beach, CA, r.m.Norman@larc.nasa.gov, phone: 757-864-6655

to retrofit this technology into today's transport aircraft fleet is also necessary to achieve the desired safety benefits, since 66% of today's transport aircraft fleet is equipped with only electro-mechanical cockpit instrumentation.

NASA's SVS concept, Figure 1, provides a real-time, unobscured synthetic view of the world for the pilot. The display is generated by visually rendering an on-board terrain database (with airport and obstacle database information as necessary) using precise position and navigation data obtained through GPS (Global Positioning System) data, with augmentation possibly from differential correction sources such as Local Area Augmentation Systems (LAAS) and Wide Area Augmentation Systems (WAAS) blended with on-board Inertial Navigation System (INS) information. This synthetic vision display can be additionally enhanced by active imaging sensors, real-time hazard information (e.g., weather and wake vortices), and traffic information as provided by Automatic Dependent Surveillance - Broadcast (ADS-B) and Traffic Information Services - Broadcast (TIS-B). Although the display representation to the pilot is synthetically derived, object detection and integrity monitoring functions (using multi-mode weather radar, radar altimeters, etc.) are envisioned to ensure sufficient accuracy and reliability for certification.

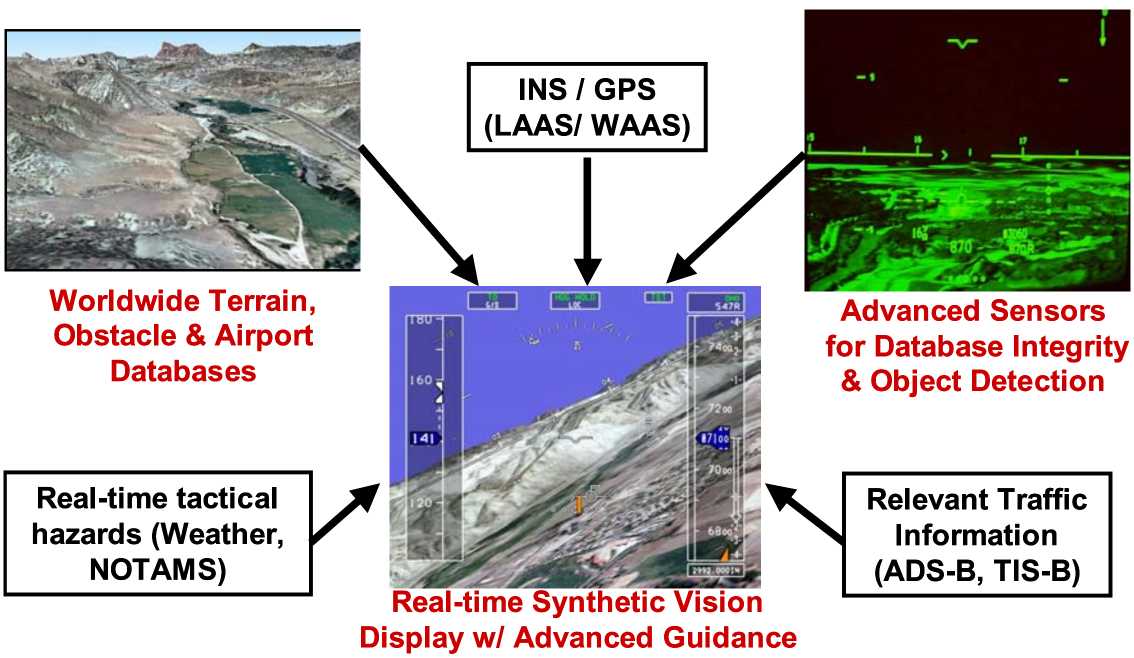

Fig. 1: Synthetic Vision System Concept

1.2 SVS Flight Test Activities

Numerous research and development activities are on-going to develop the technologies integral to the Synthetic Vision program objectives. Several flight test activities culminate the development, integration, evaluation, and demonstration of candidate Synthetic Vision (SV) display concepts in operationally-realistic flight environments.

One flight test was conducted in the vicinity of the Dallas-Ft. Worth (DFW), TX airport to confirm the potential of Synthetic Vision display concepts and to develop a path for retrofit of this technology into today's transport aircraft fleet. The retrofit technology path, brought forth from this flight test, consisted of two major thrusts:

- For aircraft with existing glass cockpit capability, simulation and flight testing showed that tactical SV display concepts hosted on displays as small as ARINC Size A/B media were viable (Reference 3). (While display media size may not be a limitation for retrofit, work is on-going to determine feasibility based on other critical factors, such as image generation, display generation, graphics rendering hardware, and cost-benefit (Reference 4). A key ingredient for success, particularly for the smaller display sizes, was pilot control of the field-of-view for the synthetic vision display concepts (Reference 3).

- For aircraft without existing glass cockpit capability, flight testing showed that tactical SV display concepts were viable using a head-up display (at least in night viewing conditions), where the SV terrain depiction is a raster-channel input to the HUD. This retrofit path takes advantage of the growing numbers of HUDs being fitted into commercial airline operations (Reference 5).

1.3 Eagle Regional County Airport

As a follow-on to the DFW test, a flight test has just been completed (August-September 2001) in the Eagle County, CO Regional Airport local area (Federal Aviation Administration (FAA) airport identifier: EGE) to evaluate tactical Synthetic Vision display concepts in a terrain-challenged operating environment. While the DFW test was a proving ground to demonstrate the concepts, the EGE area provided an ideal location to evaluate SV display effectiveness for terrain awareness due to its proximity to the mountains. Further, the technology holds potentially high direct benefit to EGE airline operations. EGE is presently the second busiest airport in Colorado based on peak-day passenger traffic with service by five major airlines on non-stop routes during the winter months from 11 major city centers.

1.4 SVS-EGE Flight Test Objectives

The two primary objectives of the SVS-Eagle County Regional Airport (EGE) flight test were as follows:

- Confirm the potential of NASA SV-Head-Up Display (SV-HUD) and Head-Down Display (SV-HDD) tactical concepts as possible retrofit or forward-fit solutions for SV technology by assessment of the pilot usability / acceptability and the situational (terrain) awareness provided.

- Evaluate pilot usability / acceptability and the situational (terrain) awareness of different methods of terrain portrayal, specifically photo-textured and generically-textured terrain database concepts, across the various SVS tactical concepts (HUD and HDD Size A/B and X with selectable field-of-view).

2. METHODOLOGY

2.1 Equipment

This flight test was conducted using the NASA/Langley Research Center (LaRC) 757 Airborne Research Integrated Experiments System (ARIES). ARIES is a modified Boeing 757-200 jetliner. The left seat in ARIES was occupied by the Evaluation Pilot (EP). The right seat was occupied by the NASA Safety Pilot (SP). The left seat included the installation of a SV-Research Display (SV-RD) and an overhead HUD projection unit. A vision restriction device was placed in the left-seat forward windscreen to block the EP's forward vision and thus, simulate instrument meteorological conditions (IMC), when needed experimentally.

The SV-RD is a Commercial Off-the-Shelf 18.1" diagonal Liquid Crystal Display, modified for installation over the forward instrument panel cluster on the left hand side of the ARIES cockpit (Figure 2). This monitor displayed all head-down display concepts for evaluation. The SV-RD covers the normal Boeing 757 captain's displays with the exception of the standby instruments. The SV-RD has 1280 vertical by 1024 horizontal pixel resolution (approximately 90 pixels per inch) with 900 nits brightness for reasonable sunlight readability in the Boeing 757 aircraft.

The left-seat, overhead projection HUD was interfaced with a Flight Dynamics HGS-4000 computer. The HGS-4000 provides a stroke-on-raster capability. The RS-343 format raster image consisted of "layers" of imagery and symbology

(Figure 3). Synthetic terrain imagery formed the so-called “Background Raster”. Raster-drawn symbology and tunnel (“Pathway-in-the-Sky”) depiction were combined to create the so-called “Foreground Raster”. HGS-4000 Primary Mode Stroke symbology overlaid the raster imagery, albeit with the compass rose symbol set removed. The field-of-view of the ARIES HUD was 22° vertical by 28° horizontal.

Fig. 2. SV-RD Installed In ARIES

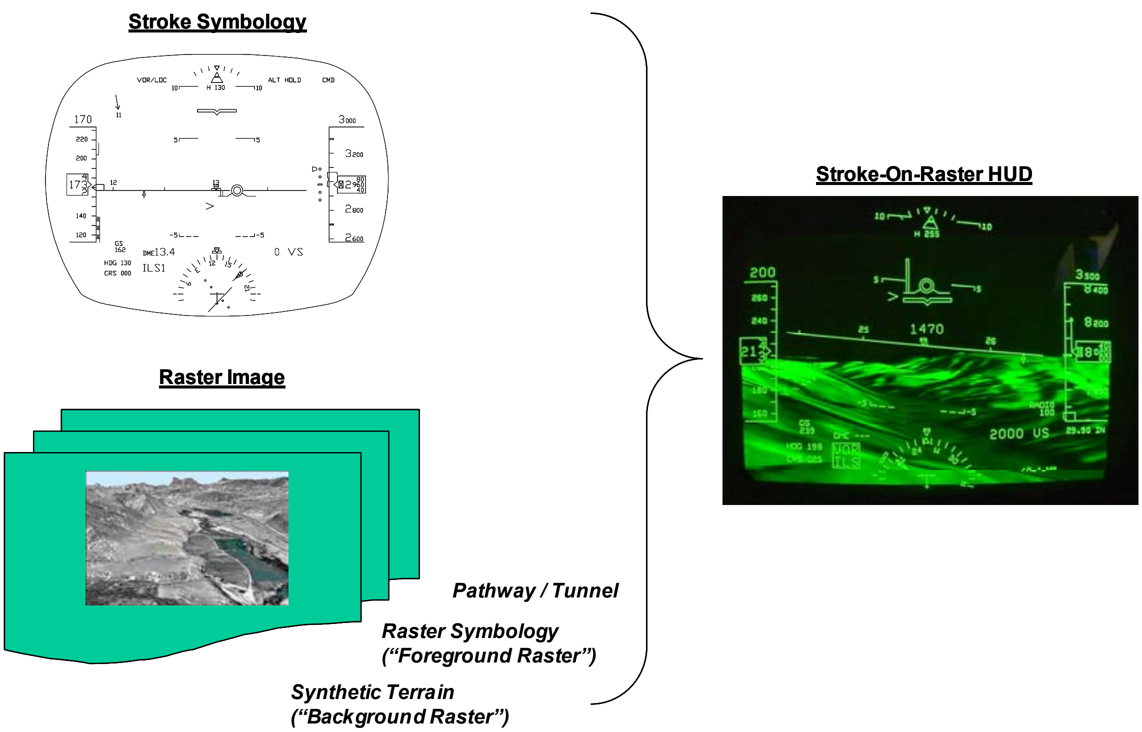

Fig. 3. HUD Stroke-on-Raster Imagery Components

HUD brightness and contrast controls were defined to allow the EP to tailor the display image. In addition, a HUD declutter button was available on the control yoke. The declutter button cycled the HUD symbology between four modes: 1) No declutter – all display elements present; 2) Foreground raster (raster symbology & tunnel) deleted; 3) Terrain and foreground raster (i.e., all HUD raster deleted); and, 4) All display elements deleted.

Field-of-view control for the NASA SV-HDDs was available to the pilot on a four position wafer switch on a center console panel. The field-of-view options were "unity", 30 deg, 60 deg, and 90 deg. The field-of-view provided at the "unity" setting changed depending upon the size of the SV-HDD to provide a conformal terrain portrayal.

The NASA SV display concepts (HDD & HUD) were generated by a dual 866 MHz processor personal computer (PC) with 1^+ Gigabytes of Random Access Memory. The PC employed the Windows NT™ operating system and a Wildcat™ graphics card to provide 1280 by 1024 anti-aliased video rendering at real-time (>30 Hz) update rates.

2.2 Terrain Database

A regional digital elevation model (DEM) of 100 nm by 100 nm was obtained with multi-resolution post-spacings varying between 1 and 3 arc-seconds. The associated vertical accuracy was between 15 and 30 meters. From this DEM, four terrain databases were created: SV-HDD Generic, SV-HDD Photo-Realistic, SV-HUD Generic, SV-HUD Photo-realistic, as described in the following.

- Each EGE terrain database was built using the Terrain Experts, Inc TerraVista Pro™ software toolset. The SV terrain databases were written to a Terrapage™ format and rendered using CG^2 Vtree.™ There are numerous TerraVista settings that affected terrain database generation, too numerous to detail here. Of particular note, level of detail switching ensured the image rendering met a 30 hz minimum update rate.

- An EGE airport model was created using Multigen Creator modeling software and placed into the SV database.

- To create the SV-HDD photo-realistic terrain database, multi-resolution imagery (ranging from 1 to 32 meters/pixel) was obtained and overlaid on the DEM. A important aspect of the photo-realistic database development was color-balancing of the various tiles in the photo imagery.

- To create the SV-HDD generic terrain database, a color mapping technique (i.e., "elevation shading") was developed and applied to the DEM. The color scheme was loosely based on Aeronautical Chart legends. The colors ranged from greens, to browns, to light tans, to off-white for the lowest to highest elevation bands. 12 bands were used, segmented into 250 meter ranges. Real-time encoding was not used.

- Because the SV-HUD is monochrome, a green-shaded generic database was created from the SV-HDD generic database. The green color intensities associated with each elevation level varied in an incremental fashion from the lowest to highest level. Thus, no two elevation levels had the same green channel value.

- To create the SV-HUD photo-realistic database, color textures were converted to monochrome green textures. An RGB file format was rendered from the photo-realistic SV-HDD database, the red and blue channels were masked out, and the image was converted back to a "ECW" format for real-time rendering.

3. FLIGHT TEST

3.1 Evaluation Tasks

Although EGE has received a "Special Airport" designation from the FAA, approach and landing procedures are typical of many airports constrained by terrain. EGE is only equipped with an offset localizer and Distance Measuring

Equipment (DME) airport navigational aides. Arrivals to both EGE runways (07 and 25) are commenced from the East under existing instrument approach procedures. To facilitate larger commercial airline operations, such as Boeing 757 aircraft, and obtain lower instrument approach minima, special Flight Management System (FMS)-based approach and landing procedures have been developed and certified for EGE. These procedures include training and equipment standards that are well above that required for the FAA-published EGE instrument approach and landing procedures.

The SVS-EGE evaluation tasks were developed by tailoring existing FAA-approved FMS-based approach and departure procedures for EGE. The tailoring did not, in any way, change the content of the approved procedures; rather, the tailoring defined procedures and constraints which aided in experimental data collection and subsequent data analysis.

Two approaches and associated departure tasks were flown:

- FMS Runway 25 Approach and Cottonwood-2 Departure:
  The tasks started on a dogleg to the final approach course, level at 13,100 ft MSL. At the final approach fix ("TALIA"), a right turn to the localizer approach course is made and the descent into the EGE local operating area is initiated. The initial descent angle is 4.5 degrees. Several descent angle changes are commanded until the aircraft is directed to a final 3 degree descent to the runway. At altitudes between 50 and 300 ft Above Field Level (AFL), the missed approach procedure ("Cottonwood-2") was flown. A reduced climb angle departure, replicating loosely the climb of a Boeing 757 in a single engine condition, was executed to provide a worse-case operational scenario but a best-case condition for terrain awareness testing.

- FMS Runway 25 Approach with Visual Arrival to Runway 7 and KREMM Departure.
  The Runway 07 approach and landing task used essentially the same FMS Runway 25 approach procedure until approximately 1500 ft AFL when a level-off and 20 degree left turn is flown into a modified downwind leg. Approximately abeam the Runway 07 threshold, a descending right turn is flown for landing. Again, the missed approach procedure ("KREMM") was executed between 50 and 300 ft AFL, using a reduced climb angle departure to provide a best-case testing condition.

3.2 Display Conditions

The flight test was designed as a comparative study against a baseline condition. The baseline was representative of the current display configuration being flown in regular airline service to EGE – the Boeing 757 Electronic Flight Instrument System (EFIS) format with a Terrain Awareness and Warning System (TAWS)-capability installed.

The baseline display (Figure 4) was presented on the SV-RD. This simulation-based approach was chosen over using the actual ARIES 757 EFIS because experimental complications were reduced. As evident in Figure 4, the baseline EFIS was intentionally not a replication of the Boeing 757 EFIS but instead, was more closely a blue-over-brown representation of the NASA SV concepts. The intent was to keep the display's symbolic information constant (e.g., pitch ladder) in the comparison across display concepts to avoid variability. TAWS was also constant across all concepts.

Six (6) NASA SV concept display configurations were evaluated. These configurations consisted of two display types (SV-HDD or SV-HUD), two SV-HDD sizes (A/B or X), and two SV terrain texturing types (generic or photo-realistic).

The range of display conditions is illustrated by the two extremes shown in Figure 5 (e.g., SV-HDD Size A/B with photo-realistic texturing) and in Figure 6 (e.g., SV-HDD Size X with generic texturing). The comparison of these displays with Figure 4 ─ the baseline display configuration – shows the intuitive nature of the SV display portrayal for terrain awareness.

In addition to SV terrain differences, several important symbolic differences were embedded in the configurations. These symbolic differences did not influence the terrain awareness properties of the display configuration evaluation but did influence the pilot's ability to precisely monitor and control the aircraft's trajectory. These differences include the airspeed and altitude format (e.g., "round-dials" or "tapes"), the presence or absence of a flight path marker, and the presence or absence of tunnel or "pathway-in-the-sky" information.

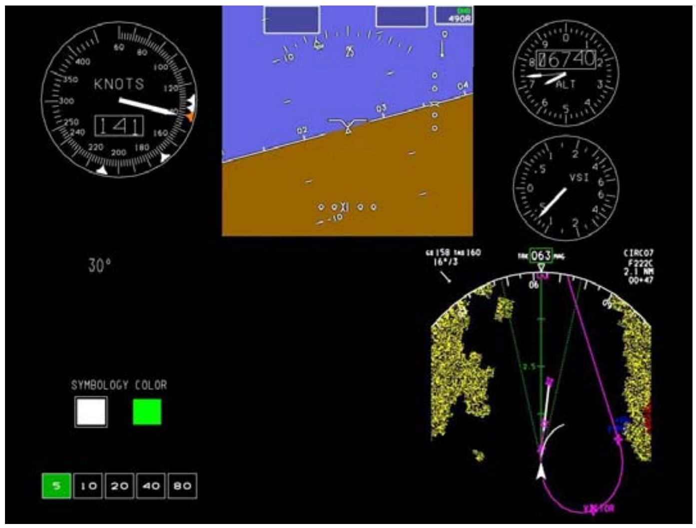

Fig. 4. Baseline Display, EFIS with TAWS

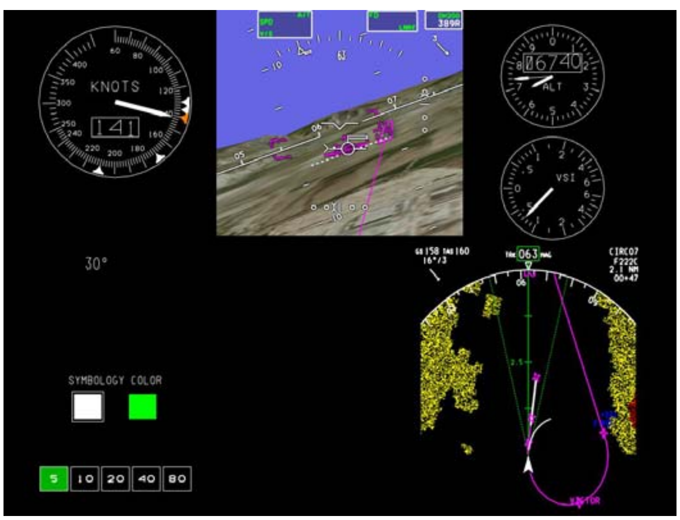

Fig. 5. Synthetic Vision Display Concept – Head Down Display Size A/B with Photo-Texturing

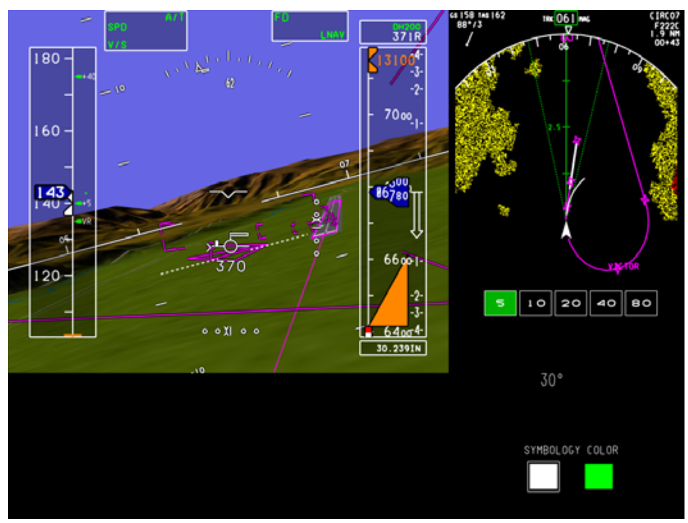

Fig. 6. Synthetic Vision Display Concept – Head Down Display Size X with Generic Texturing

3.3 Tunnel and Path Guidance Depiction

A tunnel was nominally drawn for approach guidance on the SV-HUD and SV-HDD to increase the pilot's situational awareness of the desired aircraft trajectory. The objective was to create path awareness yet not to obscure or occlude the terrain portrayal of the Synthetic Vision image by display clutter. With this objective, a "minimalist" tunnel was constructed using "crow's feet". The crow's feet were spaced at 0.2 nm along the desired path. The top crow's feet of the tunnel were only displayed up to 1.0 nm in front of the aircraft. The bottom crow's feet are linearly scaled in brightness so, by 3.0 nm from own-ship, the brightness of the bottom crow's feet was reduced to zero.

Additional guidance information for the SV display concepts was provided by a ghost airplane symbol. The ghost airplane was positioned by a modified form of pursuit guidance, documented in Reference 6, to keep the aircraft trajectory tracking the tunnel. During the missed approach tasks, the tunnel and ghost aircraft were removed and a single cue flight director based on the ship's FMS was drawn to provide pitch and roll steering commands.

3.4 Experimental Conditions

A full-factorial matrix design was established to evaluate the 6 NASA SV display concepts (SV-HUD, SV-HDD Size A/B, and SV-HDD Size X, each with generic and photo-realistic terrain) and the baseline display condition in each of the two tasks. Evaluations were flown under simulated instrument meteorological conditions. As with any flight test, some modification to this plan evolved due to weather, scheduling, and other unforeseen circumstances. Nonetheless, close to optimal results were obtained thanks to the dedicated effort of the NASA/LaRC flight test team. In addition to the full factorial matrix, other evaluations were flown (in a partial factorial form) to evaluate the influence of the tunnel or pathway-in-the-sky and the effect of visual meteorological conditions on the SV-HUD concept.

3.5 Flight Test Procedures

Each EP was a qualified 757 captain and had experience with operating procedures at EGE. Prior to the flight test deployment, all EPs received training at NASA/LaRC. Each EP flew at least two flights.

Engineering unit data was collected on all evaluations. In addition, post-run questionnaires were conducted to garner the salient subjective points immediately upon run completion. More detailed questionnaires were completed following each evaluation flight. Finally, SA-SWORD (Situational Awareness – Subjective Workload Dominance, Reference 7) questionnaires were administered at the conclusion of the EP's flights.

4. RESULTS

From 20 August to 9 September, 12 research flights totaling 51.6 flight hours were flown. Seven (7) evaluation pilots, representing 3 airlines, the FAA, NASA, and two pilots from Boeing, performed evaluations. 87 runs were conducted to evaluate the NASA display concepts of which 52 were flown to Runway 07 and 35 were flown to Runway 25.

The flight test objectives primarily involved an evaluation of the terrain awareness provided by the various display concepts. Several terrain awareness metrics were used for this purpose. While objective techniques such as SAGAT (Situational Awareness Global Assessment Technique, Reference 8) show promise, testing efficiency, data collection, and operational considerations precluded its use for this flight test and subjective measures were used exclusively.

4.1 Terrain Awareness

The primary metric for terrain awareness was a battery of post-run questionnaires, which provided a self-rating subjective assessment. While the limitations of these ratings are understood (Reference 8), the rating techniques have also proven successful (e.g., Reference 9).

After each run, the pilot was given a series of statements and numerically ranked, by adjective association, how strongly the evaluation pilot agreed or disagreed with the evaluation statement. For terrain awareness, the principle query was the statement: "It was easy to determine aircraft position with respect to terrain." The available responses ranged from

1 for "Strongly Disagree" to 6 for "Strongly Agree." The pilot was asked to elaborate on each rating through unprompted commentary. Using this subjective (albeit numerically instantiated) measure, the terrain awareness provided by the different SV display concepts was assessed by comparison against the baseline display configuration.

4.1.1 Terrain Awareness – SV-HUD Concept

The subjective measure of the terrain awareness benefit provided by the NASA SV-HUD concept is shown in Figure 7. The figure depicts the number of occurrences for a rating that an EP gave in response to the terrain awareness question for the baseline display and for the SV-HUD configuration. These data are collapsed across all EPs and tasks.

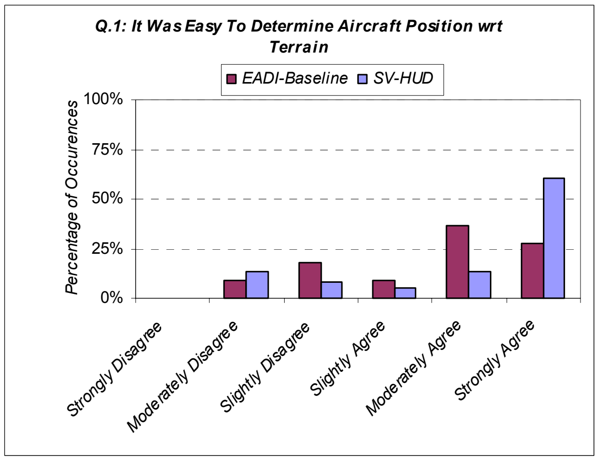

Fig. 7. Terrain Awareness Comparison Between Baseline and SV-HUD Configurations

The data of Figure 7 indicate a noticeable improvement in terrain awareness for the SV-HUD concept, as shown by the increase in occurrences of "Strongly Agree" ratings over the baseline display ratings. However, the data also shows that the SV-HUD concept, like the baseline concept, is not universally effective. Numerous pilot ratings were given where they moderately or slightly disagreed that it was easy to determine their position with respect to the terrain.

The pilot comments indicated two issues, in particular, detracted from the terrain awareness attributes of the SV-HUD configuration.

- The first comment pertained to limitations in the HUD raster image brightness (i.e., the SV terrain image). The EPs expressed concern that, the SV-HUD raster image could be washed out in high brightness backgrounds, such as direct or nearly direct sunlight viewing conditions, thus negating the terrain imagery.

- The second comment pertained to some visual artifacts in viewing the terrain portrayal in the monochromatic HUD. The pilots noted that several important features of the terrain, such as notches or rock outcroppings, were virtually invisible in the HUD image.

Each of these deficiencies ultimately relates to the database rendering techniques that were chosen for the flight test and fundamental issues associated with present-day HUD technology utilized in a daylight environment: a monochromatic display with finite raster image brightness (really image *modulation*, Reference 10). While these issues were recognized before the start of the flight test, the magnitude of the problems were not quantified. NASA research activities are now being directed to evaluate scene rendering techniques, HUD brightness capabilities, and scene augmentation techniques, such as the "Fishnet" concept being employed by Rockwell-Collins and the USAF (Reference 11), to mitigate these SV-HUD concept deficiencies.

4.1.2 Terrain Awareness – SV-HDD Concept

In contrast to the SV-HUD terrain awareness results, the subjective measures of terrain awareness for the SV-HDD concepts were significantly improved over the baseline EFIS with TAWS display configuration. The subjective rating comparison is shown in Figure 8 for the Size A/B SV-HDD concept and for the Size X SV-HDD concept compared to the baseline display configuration. The data clearly show a trend that the EP's "Strongly Agreed" that was easy to determine the aircraft position with respect to terrain with a SV-HDD concepts, particularly for the largest display media (Size X).

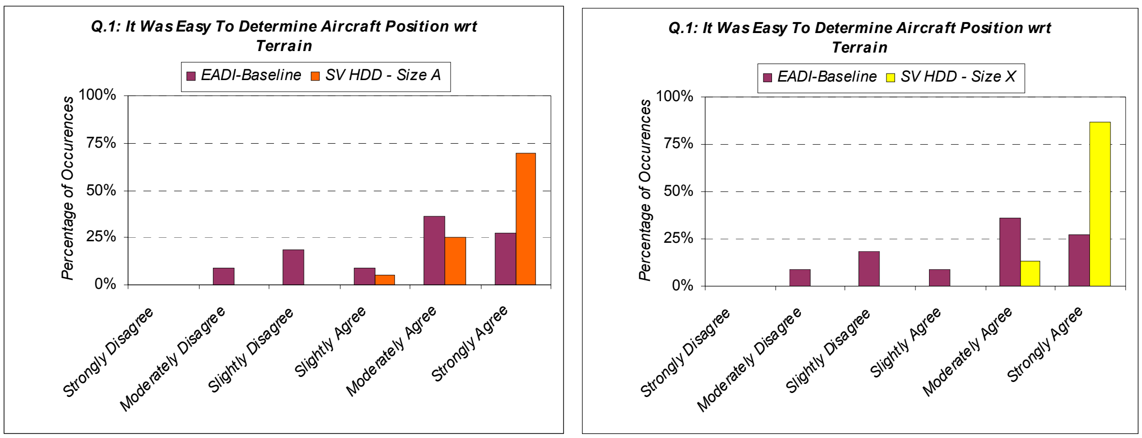

Fig. 8. Terrain Awareness Comparison Between Baseline and SV-HDDs

4.2 Terrain Awareness Confidence

Another important attribute of terrain awareness is the degree of confidence that the pilots have in the terrain information they receive. This can affect how likely they are to act on a given piece of information as compared to the need to collect further, confirming information (Reference 8). The subjective ratings related to the pilot's confidence in the terrain information conveyed by the SV-HDDs. Particularly for the Size X SV-HDD (e.g., Figure 9), pilot confidence in the SV-HDD concepts was dramatically improved over the baseline EFIS with TAWS display configuration. Particular interest should be given to the fact that ratings of "Strongly Disagree" were given when queried about the EP's confidence in the baseline display.

4.3 Display Clutter

When adding any new information to a display, concerns of clutter have to be paramount. This issue was accessed (subjectively) in the post-run questionnaire by the pilot's assessment of whether the "amount and density of display information was appropriate to the task." In the SV-HDD concepts, the worse-case configuration is the smallest display size – Size A/B configuration. For this configuration, the data shows, in Figure 10, that compared to the baseline, the addition of SV terrain did not create a clutter problem. In fact, the baseline display condition was rated poorly because the amount of information was *insufficient* to do the task. The SV terrain and other associated guidance information was found to be necessary to perform the EGE approach and departure task.

4.4 Terrain Awareness – SA-SWORD

SA-SWORD subjective comparisons were conducted across the seven display conditions (6 SV display conditions and the baseline). These data are still in the process of being analyzed for significance but the rankings to date mirror the subjective post-run-questionnaire data. The SV-Size X display configurations were unanimously ranked as providing the highest level of situational awareness of the display configurations tested and the baseline configuration, the least.

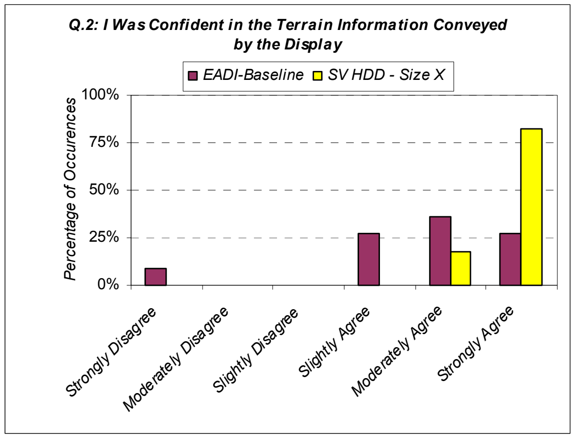

Fig. 9. Terrain Awareness Comparison Between Baseline and SV-HDD – Size X Configuration

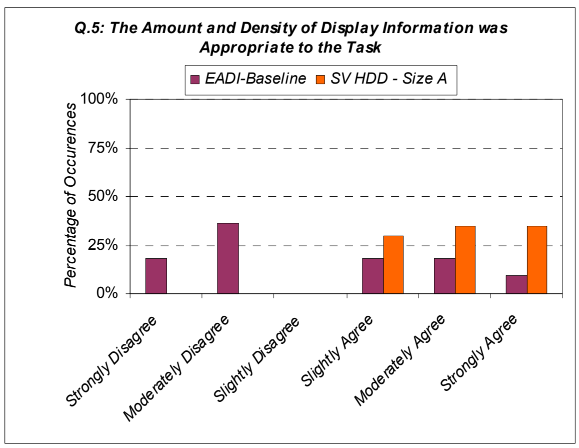

Fig. 10. Display Clutter – SV-HDD Size A/B Configuration Compared to the Baseline Display Configuration

4.5 Terrain Awareness – Texturing Effect

The post-run subjective terrain awareness data shows neither significant differences nor trend effects due to SV terrain texturing (generic or photo-realistic). Conversely, the SA-SWORD data shows a ranking preference by all EPs for the photo-realistic texturing in all display media applications in promoting situational awareness.

5. CONCLUDING REMARKS

Six NASA Synthetic Vision display concepts were tested over a 3 week period in the Eagle County Regional Airport (Colorado) local area to evaluate tactical Synthetic Vision display concepts in a terrain-challenged operating environment, including concepts for HUDs and HDDs ranging from ARINC Standard Size A through Size X. Seven pilots evaluated these displays for acceptability, usability, and situational/terrain awareness while performing existing commercial airline operating procedures. Evaluations were also flown for a baseline display configuration, simulating the EFIS with TAWS display typically flown in present-day operations.

All Synthetic Vision display concepts provided measurable increases in the pilot's subjective terrain awareness over the baseline aircraft displays. The head-down display presentations yielded significantly better terrain awareness over the baseline EFIS with TAWS display, regardless of display size. The NASA SV-HUD concept also showed some improvement in terrain awareness over the baseline EFIS with TAWS capability but some deficiencies in the SV-HUD concept were also noted which suggest further research.

ACKNOWLEDGEMENTS

This work was possible only through the collective efforts of many, many individuals too numerous to name. The authors, in particular, gratefully acknowledge the contributions of Mr. Kevin Shelton and Ms. Stella Harrison for leading the design and modification effort, including checkout and evaluation flying for the SVS team and the entire NASA/LaRC's Airborne Systems Competency who modify, maintain, and operate the NASA ARIES and associated infrastructure. The authors also are grateful for the support of NASA's Aviation Safety Program, led by Mr. Sam Morello, Synthetic Vision System Project, led by Mr. Dan Baize, and Airborne Systems Competency, led by Mr. Doug Arbuckle, assisted by Mr. Luat Nguyen.

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